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ORIGINAL PAPER

Experimental study on freezing and thawing deformation of geogrid-reinforced silty clay structure

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Abstract

Reinforcement can reduce soil's frost heave (F-H), but what kind of reinforcement condition is most beneficial to control soil's F-H if it is not clear? In this study, orthogonal experiments of freezing and thawing (F-T) to reinforced silty clay under different conditions were carried out. F-H, thaw settlement (T-S) deformation and water content of three different heights of melting clay were tested. T-S displacement was positively correlated with water content and more closely related to upper layer clay's water content. SPSS software was used to fit the regression equation of F-H and T-S displacement expressed by various influencing factors. The top three factors influencing the F-H and T-S displacement were initial water content, reinforcement spacing, and upper pressure. Taking the lowest displacement of F-H and T-S as control target, the optimal solution of all factors and target values were obtained with MATLAB software when the freezing temperature and number of freezing and thawing cycle (FTC) and upper pressure were − 15 °C, 5 times, and 30 kPa. The lowest values of F-H and T-S displacement were 3.61 mm and − 0.514 mm, respectively, when the values of the initial water content, compaction degree, and reinforcement spacing were 16%, 90%, and 25 cm, respectively.

Keywords Silty clay · Freezing and thawing cycle · Geogrid reinforcement · Displacement · Water content

Introduction

In seasonal frozen soil areas, partial liquid water in the pores of soil freezes when the temperature reaches below zero degrees Celsius, and the soil generates outward expansion which is frost heave (F-H). The pore water changes from solid to liquid with the rising of temperature, and the frozen soil melts and settles which is thaw settlement (T-S) (Bouycous 1920; Andersland and Ladanyi 2003; Qi and Ma 2010; Dong and Chen 2017). This kind of freezing and thawing (F-T) often causes serious damage to nearby buildings (Zhou and Guo 1982; Chen et al. 1996a, b). Gandahl (1980) conduct experimental research on the soil after F-T and find that increasing the initial water content will soften muddy soil and reduce its shear strength rapidly but improve the clay's shear strength. Marvin et al. (2018) consider that water content has a significant impact on soil's strength according to the results of large-scale direct shear testing. Arenson et al. (2004) and Chamberlain et al. (1990) observe that the degree of compactness of dense soil decreases void ratio after F-T, and the loose soil has opposite changing trend after F-T. Researches propose the concept of "residual void ratio" about the soil after F-T and indicate that the residual void ratio of soils will tend to be a stable value after multiple F-T. This stable value is mainly due to the severe change of soil's structure in the early stage of freezing and thawing cycles (FTC) (Viklander 1998; Shibia and Kamei 2014; Aldaood et al. 2014). Miller (1978) arrives at a conclusion that the soil will produce F-H when the load acting on the upper surface of soil structure is less than the pore pressure in the soil after FTC.

Current methods to prevent soil damage caused by freeze-thaw include replacement, compaction, chemical addition, and reinforcement. Replacement mainly uses sand, gravel, and other materials with weak water absorption to replace

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clayey soil with high water absorption. Compaction mainly improves the compactness of soil (Arora and Aydilek 2005). These two measures reduce frost heave damage by preventing frost fronts from moving upwards during frost heave, and the cost is higher. Adding chemical materials mainly include cement, lime, and fly ash to improve the frost thaw durability of soil, which may endanger the growth of surrounding crops for the chemical composition of soil (Wang et al. 2012). The antifreeze effects of these three measures will be weakened with the increase of freezing and thawing times. Reinforced soil is a kind of complex soil and net or belt, which can effectively improve the bearing capacity of the soil and strengthen the stability of the soil by adding reinforcement in the soil in a proper way, giving full play to the tensile strength of the reinforcement material and the compressive strength of the soil (He 2000). The interlocking action of the geogrid can effectively control uneven settlement of the road surface by transmitting the horizontal strain to the geogrid (Zhang and Zhang 1994). Chen et al. (1996a, b) conduct freezing test on the reinforced soils, and the results show that the F-H amount is significantly reduced compared to the soil without reinforcement. Reinforced materials can restrain the F-H of soil, make the structure of soil stronger, improve the strength of soil, and decrease the deformation of F-H. Wang et al. (2010) carry out a freezing test on the reinforced clay; the results show that the geogrids appear tensile strain which is beneficial to reduce the horizontal F-H force of the soil and decrease the frost damage to clay. Zhao et al. (2014) consider that the shear strength of reinforced clay structure undergone F-T action will decrease with the increasing of initial water content and increase with the increasing of compaction degree when they change in a certain range. Cai et al. (2016) recognize that reinforcement can improve the strength of soft soil after F-T and effectively reduce structural T-S. Ghazavi and Roustaie (2010) find adding steel fibers or geotextiles to the clay will obviously improve the soil's ability to resist F-T damage. Therefore, geotechnical reinforcement has increasingly become an important measure in the construction of project to prevent the F-T-based degradation in soil structures. Land degradation neutrality is part of the Sustainable Development Goals adopted by United Nations in 2015. Physical land degradation is one of land degradation types which involve the movement and/or rearrangement of soil particles without changing their chemical composition (Keesstra et al. 2016, 2018). So, the research of geotechnical reinforcement will contribute to achieve the United Nations Goals for Sustainability and the prevention of land physical degradation.

However, there are many factors affecting the F-T damage of reinforced soil, such as soil structure, compaction, moisture content, number of reinforcements, etc. Nowadays, most researchers focus on the influence of one or more several factors on the soil, and few studies considering the comprehensive roles of these influencing factors, which are disadvantageous to the effective control of soil freezing and thawing. The influence of various factors on the performance of soil after F-T is still unclear. Therefore, in this study, the F-T experiments on reinforced silty clay under different initial water content, compaction degree, reinforcement spacing, freezing temperature, number of FTC, and upper pressure conditions were used to determine the F-H, T-S deformation and the water content of three different heights of melting clay. SPSS software was used to fit F-H and T-S displacement regression equations which were expressed by various influencing factors, solving the optimal values of various factors when the F-H and T-S displacement were lowest by MATLAB software which provides a theoretical reference for actual engineering construction design in seasonal frozen soil areas.

Materials and methods

Experimental materials

The soil samples were taken from the experimental base of Shenyang Agricultural University. Bidirectional stretched plastic geogrid (TGSG30–30, Lianyi Engineering Plastics Co., Ltd., Feicheng, Shandong, China) was used to be the reinforcement material (shown as Fig. 1 and Table 1). The F-T experimental equipment was a modified freezer (internal temperature control range is − 35 °C − +20 °C, accuracy is 0.1 °C). According to Code for Design of Building Foundation (2017), the corresponding basic physical indicators of soil sample were shown in Table 2, and the soil sample was classified into low liquid limit silty clay.

Preparation of experimental specimen

According to Technical Specifications for Construction of Highway Reinforced Earth Engineering (1991). Firstly, leveled and compacted the bottom soil in the box. Secondly, the geogrid shall be laid on the surface of the compacted bottom soil and shall not be bent. Thirdly, laid the soil on

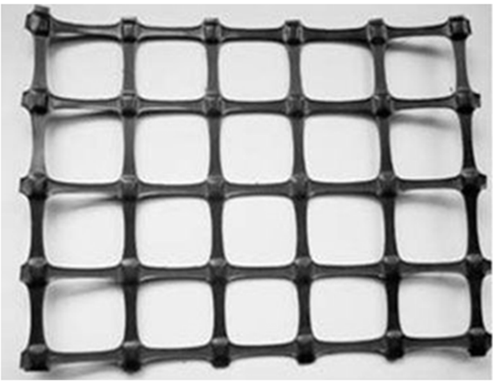


Fig. 1 Bidirectional stretched plastic geogrid

Table 1 Properties of geogrids

Rib direction	Tensile strength (kN·m^{-1})	Aperture size (mm)	Density (g·cm^{-3})	Polymer type
Longitudinal	30	35 × 35	400 ± 40	Polypropylene
Transverse	30			

the geogrid and leveled and compacted it. If there were more than one layer of geogrid, we should one or two times repeat Step 2 and 3 according to the real reinforcement layers. In order to prevent the movement and deformation of geogrid during the compaction of the upper fill, both ends of the geogrid were extended out of the box and fixed on the outside (shown as Fig. 2).

(**a**) Soil compaction (**b**) Geogrid laying

Initial water content adjustment

After the clay samples were air-dried, the water content is 9%. In order to investigate the effect of different initial water content on the properties of the reinforced clay after F-T, it was necessary to add water to the air-dried clay samples. The required water mass was calculated according to Eq. (1).

$$m_w = \frac{0.0.\mathrm{x}(\omega - \omega_0)}{1 + 0.01\omega_0}\mathrm{x}m \tag{1}$$

water mass required for clay samples, g; is the initial water content of the prepared clay, %; is the water content of air-dried clay samples, %, its value is 9; is the mass of clay with a water content of 9%, g.

Arrangement of different reinforcement spacing

In order to investigate the influence of the reinforcement spacing on the properties of the reinforced clay after F-T, five kinds of specimens with different geogrid spacing were prepared. The distance between first layer and the top of specimen was 4 cm. Three-layer geogrids were arranged in the specimens when the reinforcement spacing was 15 cm. Two-layer geogrids were arranged in the specimens when the reinforcement spacing were 20 cm, 25 cm, 30 cm, and 35 cm. The geogrid was cut into a rectangle shape in the size of width 160 mm and length 300 mm before testing. The placement position of corresponding geogrids in the testing specimen was shown in Fig. 3.

Determination of different compaction degrees

In order to investigate the effect of compaction degree on the properties of reinforced clay after F-T, the loose clay was compacted by manual compaction with self-made compactor (shown as Fig. 2(a)) and the compaction degree K of all five kinds of specimens was calculated according to Eq. (2).

$$K = \frac{\rho_d}{\rho_{d\max}} \times 100\% = \frac{\frac{m'}{V(1+\omega)}}{\rho_{d\max}} \times 100\% \tag{2}$$

where, m' is the mass of the test piece required to prepare the corresponding compaction, g; is the initial water content of the prepared clay to be compacted, %; is the volume of the test chamber, cm^3, its value is 2.4×10^4; $\rho_{d\max}$ is the maximum dry density of the clay samples, g·cm^{-3}, and its value is 1.69.

The required filling mass m for each specimen was:

$$\begin{aligned} m' &= \rho_{d\max}K(1+\omega)V = 1.69 \times 2.4 \times 10^4 K(1+\omega) \\ &= 4.056 \times 10^4 (1+\omega)K \end{aligned} \tag{3}$$

Displacement and water content determination

The F-H and T-S displacement of the reinforcement clay were measured by the strain measurement and analysis system (DM-YB1820, Nanjing Danmo Electronic Technology Co., Ltd., Nanjing, Jiangsu, China) and strain type linear displacement sensor (YWD-30, Nanjing Danmo Electronic Technology Co., Ltd., Nanjing, Jiangsu, China) when the last F-T was finished in the given freezing temperature and number of FTC and upper pressure. The F-H displacement is the vertical deformation value of clay's upper surface after the last freezing compared to its position before the F-T. The T-S displacement is the vertical deformation of clay's upper surface after the last thawing compared to before the F-T. Displacements of the center point and four surrounding symmetry points of the reinforced clay's surface were measured. The F-H and T-S displacement were adopted as the average of this five values, respectively. After the FTC, the water content values of reinforced clay's in three different heights (the upper

Table 2 Basic physical indicators of soil sample

Particle content of each particle size range (%)		Liquid limit (%)	Plastic limit (%)	Plasticity index		Maximum dry density (g·cm^{-3})	Optimum water content (%)
< 0.005 mm 28.1	0.005–0.075 mm 58.7	> 0.075 mm 13.2	32.4	17.8	14.6	1.69	20.1

Fig. 2 Placement of geogrid in specimen


(a) Soil compaction (b) Geogrid laying

layer, middle layer, and lower layer were 5 cm, 20 cm, and 35 cm distance to the top, respectively) were measured. Three points were taken to measure the water content at each height of the soil layer, and the average value of these three points was used to represent the water content of the corresponding soil layer. The difference in water content of each layer represented the change of liquid water distribution along the height direction after F-T. Through analyzing the influence of reinforcement on the flowing of liquid water after F-T, the effects of different reinforcement conditions on the displacement of clay were discussed.

Experimental design

In this study, the initial water content (x_1), compaction degree (x_2), reinforcement spacing (x_3), number of FTC (x_4), freezing temperature (x_5), and upper pressure (x_6) were selected to conduct orthogonal experiments on FTC. The values of each influencing factor and level were shown in Table 3.

In this study, the horizontal and actual values of the six independent variables are given in Table 3. The orthogonal experiments were used to indicate the influence of initial water content, compaction degree, reinforcement spacing, number of FTC, freezing temperature, and upper pressure on clay's F-H and T-S. Then, using SPSS software to obtain regression equations based on the results of orthogonal experiment and performed variance analysis. Finally, MATLAB software was used to optimize the initial water content, compaction degree, and reinforcement spacing to obtain the minimum displacement of the clay in the given FTC conditions of freezing temperature, number of FTC, and upper pressure. The regression equation was shown as:

$$y_1 = C + \sum_{i=1}^{6} C_i x_i + \sum_{i=1}^{6} C_{ii} x_i^2 + \sum_{i=1}^{5} \sum_{j=i+1}^{6} C_{ij} x_i x_j \ (n = 1, 2) \tag{4}$$

where, y_1 is F-H displacement, mm; y_2 is T-S displacement, mm; x_1 is initial water content, %; x_2 is compaction degree, %; x_3 is reinforcement spacing, cm; x_4 is number of FTC, times; x_5 is freezing temperature, °C; x_6 is upper pressure, kPa; C、C_i、C_{ii} and C_{ij} is the main item in the equation, constant term, and regression coefficient of quadratic term and interaction term.

Results and discussion

Orthogonal experimental results

The experimental results were shown in Table 4. Water contents in the upper, middle, and lower parts of clay ranged between 21.17%–27.27%, 21.10%–27.31%, and 21.53%–29.22%, respectively. The range of F-H and T-S displacements were from − 4.59 mm to 7.42 mm and − 6.57 mm to 6.39 mm, respectively.

where, x_1 is initial water content, %; x_2 is compaction degree, %; x_3 is reinforcement spacing, mm; x_4 is number of FTC, times; x_5 is freezing temperature, °C; x_6 is upper

Fig. 3 Schematic diagram of reinforcement (unit: cm)

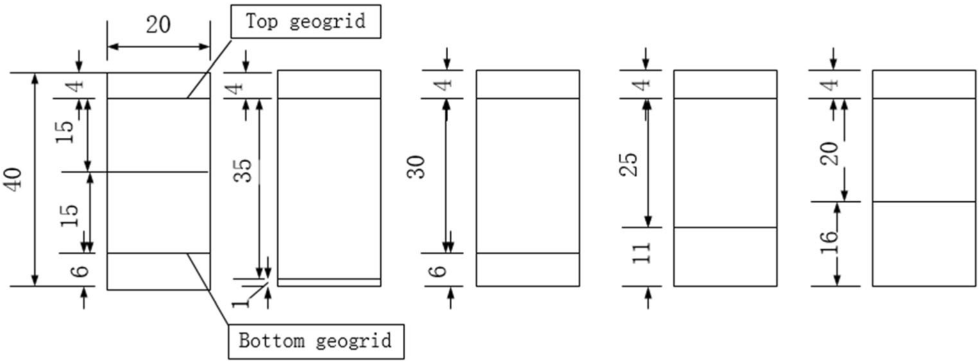


Table 3 Factors and levels used in the orthogonal experiment

Factors Levels	x_1 (%)	x_2 (%)	x_3 (cm)	x_4 (Times)	x_5 (°C)	x_6 (kPa)
1	28	96	35	9	−5	50
2	24	93	30	7	−10	40
3	20	90	25	5	−15	30
4	16	87	20	3	−20	20
5	12	84	15	1	−25	10

pressure, kPa; y_1 is F-H displacement, mm; y_2 is T-S displacement, mm; ω_U, ω_M, and ω_L are the water content of the upper, middle, and lower parts in the clay after FTC, respectively, %.

F-H and T-S displacement of clay structure after F-T

The data of number 19 and 22 F-H displacement in Table 4 were negative values which indicated that the reinforced clay generated settlement after one F-T. Meantime, the F-H displacements of reinforced clay normally increased with the increasing of initial water content after one F-T which could be obtained from data of number 22, 19, 11, 8, and 5 F-H displacement in Table 4. The clay's pores were filled with liquid water and air. Most of the clay's pores were filled by water when the initial water content was high. Oppositely, most of the clay's pores were filled with air when the initial water content was low. Clay structure had not enough time to uptake liquid water from water supply system during the first freezing process. A large amount of water changed into ice crystals, filled the pores and squeezed the original air, and made the clay particles expand outward which produce high initial water content clay's F-H. On the contrary, lots of the air were compressed for negative temperature; meantime, upper pressure and weight of clay reduced the volume of pores and caused the clay particles to squeeze inward which generate low initial water content clay's settlement after first freezing.

The data of number 16, 17, 18, and 21 T-S displacement in Table 4 were positive values which indicated that the reinforced clay generated heave deformation after FTC. The volume of air in the clay pores were replaced by water after several times F-T for the clay structure in the condition of low initial water content and high compaction degree. However, the volume of pores was relatively small in the high

Table 4 F-H, T-S displacements and three layer's water content results after FTC based on orthogonal experiment

Runs	x_1 (%)	x_2 (%)	x_3 (cm)	x_4 (Times)	x_5 (°C)	x_6 (kPa)	y_1 (mm)	y_2 (mm)	ω_U (%)	ω_M (%)	ω_L (%)
1	28	96	35	9	−5	50	4.86	−6.33	27.27	27.13	27.33
2	28	93	30	7	−10	40	4.11	−6.57	26.45	25.91	26.77
3	28	90	25	5	−15	30	2.85	−5.94	24.86	24.55	26.13
4	28	87	20	3	−20	20	0.72	−5.91	25.03	24.21	24.81
5	28	84	15	1	−25	10	1.08	−6.21	24.44	23.98	24.86
6	24	96	30	5	−20	10	3.66	−1.95	22.42	22.95	24.33
7	24	93	25	3	−25	50	3.00	−4.65	23.62	23.55	22.28
8	24	90	20	1	−5	40	0.81	−3.93	22.31	22.39	22.48
9	24	87	15	9	−10	30	2.05	−4.35	26.03	25.95	27.04
10	24	84	35	7	−15	20	4.32	−3.45	25.33	24.44	27.12
11	20	96	25	1	−10	20	0.80	−2.37	21.17	21.62	22.22
12	20	93	20	9	−15	10	5.45	−0.93	25.85	25.66	27.93
13	20	90	15	7	−20	50	1.32	−1.02	25.64	25.48	26.63
14	20	87	35	5	−25	40	4.35	−3.72	23.94	24.55	24.03
15	20	84	30	3	−5	30	4.98	−1.83	23.23	22.89	23.58
16	16	96	20	7	−25	30	7.42	6.39	22.42	23.82	24.38
17	16	93	15	5	−5	20	6.02	1.35	23.08	23.22	23.82
18	16	90	35	3	−10	10	3.24	3.87	21.62	22.54	22.11
19	16	87	30	1	−15	50	−4.59	−4.32	21.81	21.52	21.53
20	16	84	25	9	−20	40	4.11	−5.22	26.41	26.33	27.11
21	12	96	15	3	−15	40	2.88	2.19	22.82	22.51	22.76
22	12	93	35	1	−20	30	−3.60	−2.88	21.21	21.10	21.82
23	12	90	30	9	−25	20	5.14	−2.43	25.52	27.31	29.22
24	12	87	25	7	−5	10	4.73	−2.34	24.74	25.12	25.90
25	12	84	20	5	−10	50	0.84	−3.96	23.73	23.63	24.20

compaction degree clay, and limited liquid water could be transferred into the clay after freezing. Meantime, high compaction degree insured the clay structure had enough resisting pressure ability even after thawing. Finally, the thawing deformation was less than the heave deformation after multiple F-T which leaded the F-T displacements of the low initial water content and high compaction degree clay structure to be positive values. Uzer (2016) conducted F-T experiments on clayey sand, sandy silt with clay, and sandy silt in conditions of different initial water content and found that soil with lower water content produced higher strength after FTC which was a benefit for the carrying capacity of the soil. The amount of F-H and T-S of the reinforced clay would gradually increase with the increasing of number of FTC, and this kind increasing trend would gradually decrease after several times of FTC which was consistent with the results of Mao et al. (2009) and Feng et al. (2016).

Relationship between clay's T-S displacement and water content after F-T

The migration of soil water occurred during the FTC which resulted in uneven distribution of water at each height and caused the difference of final F-H and T-S displacement. The values of migration were related to initial water content, compaction degree, reinforcement spacing, and number of FTC, etc. According to the testing results in Table 4, the effects of the water content in the upper, middle, and lower layers on the T-S displacement were analyzed after F-T which was shown in Fig. 4 (a), (b), and (c): (a) Upper layer water content and displacement, (b) middle layer water content and displacement, and (c) lower layer water content and displacement.

According to the relationship between water content and T-S displacement shown in Fig. 4, the change of T-S displacement was positively related to the water content and more closely related to the change of the water content in the upper part of the clay. The reinforced clay only expressed a certain T-S deformation when the average water content was higher than 23.37%, and the T-S displacement almost increased with the increasing of average water content. The reinforced clay occurred, both T-S and F-H deformation, when the water content was smaller than 23.37% which was mainly decided by the initial water content and compaction degree. Wang et al. (2009) also recognized that the compression of clay increased with the increasing of water content after F-T.

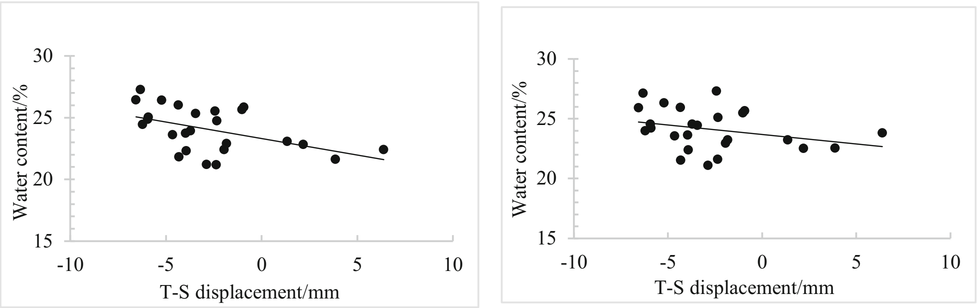
Changes of water content in various layers of clay structure after F-T

The changes of the water content in different layers were analyzed based on the results of Table 4. For dense clay, the void penetration of clay would be enhanced with the increasing of reinforcement amount (reduction of reinforcement spacing) which was beneficial for the infiltration of upper water after F-T and the reduction of the water content in the upper layer. Taking 5 different reinforcement spacing clay samples with 96% compaction degree as research objects, the arrangement of water content in three layers from low to high were ω_U, ω_M, and ω_L for 20, 25, and 30 cm reinforcement spacing, ω_M, ω_L, and ω_U for 15 cm reinforcement spacing, and ω_M, ω_U, and ω_L for 35 cm reinforcement spacing. It could be found that adding grille was beneficial for water infiltration of higher compaction degree clay. But the reinforcement spacing could not be too small. On the contrary, for loose clay, the pores in the clay and the gaps between the upper and lower sides were relatively high. The water would rise to the frozen surface along the gaps from the bottom of the clay under the action of the upper capillary when the clay was freezing. The upper layer had a larger water content in the frozen state. During the melting process, the frozen clay melted unidirectionally from top to bottom. The upper clay melted firstly with the increasing of temperature. The ice crystals in the lower clay could not melt in a short time which would make the upper water unable to infiltrate in time, resulting in the water content in the upper clay not reducing quickly. The connectivity of clay voids would decrease with the increasing of reinforcement amount when the compactness of clay was low and the void ratio was large. It was not conducive to the infiltration of water and decreasing the water content in the upper layer clay. For 84% compaction degree clay with 5 different reinforcement spacing after FTC, the arrangement of water content in three layers from low to high were ω_L, ω_U, and ω_M for all samples. Zhang et al. (2014) carried out F-T experiments to silty clay in conditions of water supply and obtained that the water content in the clay increased with the increasing of FTC times which was consistent with the change trend of water content in Table 4.

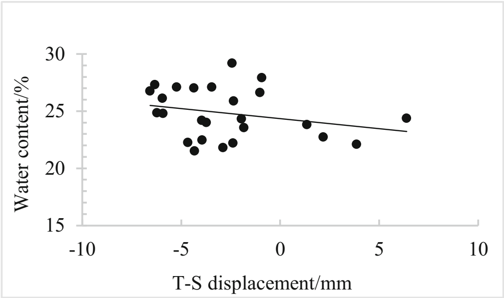
Regression analysis and optimal value solving

In order to analyze the comprehensive influence of various factors on the F-H and T-S displacement, it was necessary to establish a regression equation expressing the influence of multiple factors on the F-H and T-S displacement. In this study, the multiple linear regression equation was established by SPSS statistical analysis software according to the data of F-H and T-S displacement under different FTC conditions. In order to analyze the interaction between various factors, the measured F-H and T-S displacement were taken as dependent variables, and the water content, compaction degree, reinforcement spacing, number of FTC, freezing temperature, and upper pressure were taken as independent variables. The influence of each factor on displacement changes were analyzed by multiple quadratic linear regressions. The regressions for F-H and T-S displacements were shown as Eq. (5) and (6).

Fig. 4 Relation curve of T-S displacement and water content



(a) Upper layer water content and displacement (b) Middle layer water content and displacement



(c) Lower layer water content and displacement

$$y_1 = 125.657-3.655x_1-0.665x_2-2.486x_3+4.977x_4-1.561x_5-1.013x_6 + 0.146x_1x_3-0.106x_1x_4+0.03x_1x_5+0.05x_1x_6-0.151x_3x_4-0.006x_3x_5 + 0.002x_3x_6+0.028x_4x_5+0.02x_4x_6+0.02x_5x_6-0.012x_1^2 \tag{5}$$

$$y_2 = 181.365-6.01x_1-0.712x_2-2.02x_3-3.902x_4-0.55x_5-1.247x_6 + 0.117x_1x_3+0.189x_1x_4-0.046x_1x_5+0.078x_1x_6-0.132x_3x_4+0.007x_3x_5 + 3.74\times10^{-4}x_3x_6-0.122x_4x_5+0.015x_4x_6+0.04x_5x_6-0.029x_1^2 \tag{6}$$

where, x_1 is initial water content, %; x_2 is compaction degree, %; x_3 is reinforcement spacing, cm; x_4 is number of FTC, times; x_5 is freezing temperature, °C; x_6 is upper pressure, kPa; y_1 is F-H displacement, mm; and y_2 is T-S displacement, mm.

Tables 5 and 6 showed that *P* values of the regression models about F-H and T-S displacements were smaller than 0.01, and *F* values of the regression models about F-H and T-S displacements were bigger than 2. This indicated that the regression analysis about F-H and T-S displacements reached a very significant level, and the equations about F-H and T-S displacement had statistical significance.

Where, "*" means generally significant difference at $P<$ 0.05 level; "**" means extremely significant difference at $P<$ 0.01 level; x_1 is initial water content, %; x_2 is compaction degree, %; x_3 is reinforcement spacing, cm; x_4 is number of FTC, times; x_5 is freezing temperature, °C; x_6 is upper pressure, kPa; and *F*values of F-H and T-S displacement regression models are 6.725 and 7.457, respectively.

Table 5 indicated that the influence of reinforcement spacing, upper pressure, and the interaction between initial water content and reinforcement spacing on the F-H displacement of clay were extremely significant, and the initial water content,

Table 5 Significant analysis of the influence of various factors on F-H displacement of freezing clay

Source	Coefficient	*P*value	Significance	Source	Coefficient	*P*value	Significance
model		0.008	**	x_1x_5	0.030	0.499	
x_1	− 3.655	0.062	*	x_1x_6	0.050	0.020	*
x_2	− 0.665	0.013	*	x_3x_4	− 0.151	0.023	*
x_3	− 2.486	0.002	**	x_3x_5	− 0.006	0.357	
x_4	4.977	0.226		x_3x_6	0.002	0.722	
x_5	− 1.561	0.162		x_4x_5	0.028	0.722	
x_6	− 1.013	0.009	**	x_4x_6	0.020	0.047	*
x_1x_3	0.146	0.003	**	x_5x_6	0.020	0.092	
x_1x_4	− 0.106	0.340		x_1^2	− 0.012	0.441	

Table 6 Significant analysis of the influence of various factors on T-S displacement of melting clay

Source	Coefficient	*P*value	Significance	Source	Coefficient	*P*value	Significance
model		0.006	**	x_1x_5	− 0.046	0.360	
x_1	− 6.01	0.014	*	x_1x_6	0.078	0.004	**
x_2	− 0.712	0.016	*	x_3x_4	− 0.132	0.059	
x_3	− 2.02	0.008	**	x_3x_5	0.007	0.360	
x_4	− 3.902	0.385		x_3x_6	0.000374	0.944	
x_5	− 0.55	0.639		x_4x_5	− 0.122	0.190	
x_6	− 1.247	0.006	**	x_4x_6	0.015	0.140	
x_1x_3	0.117	0.016	*	x_5x_6	0.04	0.012	*
x_1x_4	0.189	0.148		x_1^2	− 0.029	0. 123	

compaction degree, the interaction between initial water content and upper pressure, the interaction between reinforcement spacing and number of FTC, and the interaction between number of FTC and upper pressure had a significant influence on the F-H displacement of clay. In the regression equation of F-H displacement, the standardized coefficients of initial water content, compaction degree, reinforcement spacing, number of FTC, freezing temperature, and upper pressure were − 7.633, − 1.041, − 6.489, 5.196, − 4.075 and − 5.290, respectively. The order of each factor affecting on the target value could be expressed by the absolute value of the standardization coefficient. Thus, the factors affecting the F-H displacement from high to low were initial water content, reinforcement spacing, upper pressure, number of FTC, freezing temperature, and compaction degree, respectively. When only the main effect was considered, the soil F-H displacement was inversely proportional to the soil compaction degree (Wang et al. 2015). However, the clay has an interaction after reinforcement. The influence of the reinforcement spacing was more obvious than the compaction degree. The F-H displacement was lower for the clay structure with smaller reinforcement spacing, lower compaction degree, and lower initial water content. The influence of the reinforcement spacing on the F-H displacement was more significant than the action of compaction degree.

Table 6 showed that the influence of reinforcement spacing, upper pressure, and the interaction between initial water content and upper pressure on the T-S displacement of clay were extremely significant, and the initial water content, compaction degree, the interaction between initial water content and reinforcement spacing, and the interaction between freezing temperature and upper pressure had a significant influence on the T-S displacement of clay. In the regression equation of T-S displacement, the standardized coefficients of initial water content, compaction degree, reinforcement spacing, number of FTC, freezing temperature and upper pressure were − 10.641, − 0.946, − 4.471, − 3.455, − 1.217, and − 5.521, respectively. The factors affecting the T-S displacement from high to low were initial water content, upper pressure, reinforcement spacing, number of FTC, freezing temperature, and compaction degree, respectively. Compared to the effect of the F-H displacement, upper pressure had more obvious influence on the T-S displacement than reinforcement spacing.

In order to further understand the influence of each factor on the displacement change, it was necessary to optimize solving the equations about F-H and T-S displacement. Wang et al. (2009) obtained that the amount of soil F-H increased with the decreasing of freezing temperature. Hao (2017) recognized that the resilience modulus of soil was inversely proportional to the number of FTC. Zheng and Zhao (2013) found that the F-H displacement of soil under open system conditions was larger than that under closed-system conditions. Fu and Wang (2010) confirmed that the amount of F-H displacement increased with the increasing of the number of FTC, but the rate of increasing gradually decreased. Therefore, the optimization goal was to obtain the minimum values of F-H and T-S displacement in the conditions of given freezing temperature, upper pressure, and number of FTC based on the fitted regression equation. According to the calculation results of MATLAB software, the optimized combinations of responses of reinforced clay with initial water content of 16%, compaction degree of 90%, and reinforcement spacing of 25 cm were achieved at a freezing temperature of − 15 °C, a number of FTC of 5 times, and a upper pressure of 30 kPa. The minimum values of F-H and T-S displacement were 3.61 mm and − 0.514 mm, respectively. Therefore, it is possible to analyze the soil properties (initial water content, compaction degree, etc.) in different regions or other kind of soils according to the optimal solution and provide a reference for the actual project.

Conclusion

The results of F-H and T-S displacement and water content which measured by orthogonal test and analyzed with SPSS software showed that the change of clay's displacement was mainly affected by the water content in clay's upper layer, and the change of displacement was positively consistent with the water content. Increasing compaction degree and reducing the initial water content and reinforcement spacing could decrease the water content in the upper layer and reduce clay's F-H and T-S displacement. The influence of reinforcement spacing, upper pressure, and the interaction between initial water content and reinforcement spacing on the F-H displacement of clay were extremely significant. Reinforcement spacing, upper pressure, and the interaction between initial water content and upper pressure had extremely significant influence on the T-S displacement of clay. The factors influencing the F-H and T-S displacement in the top three were initial water content, reinforcement spacing, and upper pressure, respectively.

Using MATLAB software to optimize all the reinforcement parameters for reinforced clay in given solving FTC conditions with selected response variables. In conditions of − 15 °C freezing temperature, 5 times FTC and 30 kPa upper pressure, the minimum values of F-H and T-S displacement were 3.61 mm and − 0.514 mm when initial water content, compaction degree, and reinforcement spacing were 16%, 90%, and 25 cm, respectively. Reasonable design of reinforcement clay in different FTC conditions can be obtained based on the optimal solution of the regression equations about clay's F-H and T-S displacement after F-T, which provide theoretical basis for the control of F-H and T-S damage of reinforced geogrid structures in seasonal frozen area. At present, the geogrid reinforced structures are widely used in soft foundation treatment of railway and highway, reinforced retaining walls, and reinforced steep slope projects. Further researches will provide new research mentalities and methods for solving the abovementioned problems of the above engineering structures in the seasonal frozen regions.

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